PROCEDURES FOR THE COLLECTION, ANALYSIS, AND INTERPRETATION OF EXPLOSION-PRODUCED DEBRIS

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ABSTRACT

As predictive models for explosion-produced debris become available, a need exists for experimental data against which these models may be validated. In addition, a firm database is required for the definition of debris-related explosive-safety quantity-distances. In the past, the debris collection and recording techniques used in tests have varied from the inadequate to the obsessive. It became evident during recent attempts at collating debris data that, independent of the thoroughness of approach, debris information was often difficult or impossible to analyze such that test-to-test comparisons could be made. A controlled and well-defined methodology was needed to overcome these problems. At the request of the NATO AC/258 Storage Sub-Group, the authors have prepared this document which, it is hoped, will form the first step in achieving some uniformity of approach to debris data collection and recording. The paper provides a bibliography of currently available explosion-debris information and discusses various methods that may be used to collect and catalog debris information. As the data collection process starts at the test planning stage, it is at this point that the recommendations commence. The paper concludes by presenting and discussing algorithms that may be used to analyze the data.

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1. INTRODUCTION

Consider a hypothetical scenario that is based on the authors' experience. Imagine an explosive storage igloo that is loaded to a high density with mass detonating explosives. An accident occurs, causing the initiation of the structure's contents. As a result, the igloo is completely destroyed and surrounding structures sustain varying amounts of damage. An examination of the damage shows that it has been caused not only by the blast but also by fragmentation from the explosion source and building debris produced by the event. At the magazine separation distances extant, the current regulations consider that the major damage mechanism should be blast. However, it is obvious that debris from the igloo and fragmentation from its contents have generated a significant proportion of the observed effects. As a result of the investigation of this accident, it was found that the density of hazardous debris did not fall to an acceptable level within a range of 1200 meters. Current standards would indicate that "There is a minor hazard from projections at 400 meters. This is tolerable for ... main public traffic routes ... or all inhabited buildings" [1]. It is clear from this that a greater knowledge of the explosives generation of debris is required.

It is unfair to say that this problem has not already been recognized**;** over the last decade much work has been done by the authors and others to address it. Internationally, trials have been carried out to determine the debris generated by explosions in test structures [2-6]. On a national basis, analyses have been made of debris data from explosives accidents. From such trials and accident investigations, improvements to both national and international standards have been made and, for some circumstances, models developed to support risk assessment. As the result of their involvement in many of the above activities, the authors were invited by the Ad Hoc Technical Working Party of the Storage Sub-group of the NATO Panel of Experts on the Safety Aspects of Transportation and Storage of Military Ammunition and Explosives, AC/258 to "generate a paper on the overall subject of debris collection and analysis" [7].

In this paper, the authors discuss the thought processes behind the following areas: planning for unplanned events, consistency of approach, and credible scenarios. We then advise the need for the reader to consider and define the specific objectives to satisfy his requirement(s), whilst bearing in mind the broader long term needs of the safety community. We describe the various methodologies for the collection of debris data and conclude by describing the means by which such data should be analyzed in order to meet the desired objectives.

2. PLANNING FOR UNPLANNED EVENTS

An accident in an explosives facility is an unplanned event for which contingency plans must be made. To minimize the risk to personnel and property, an understanding of the potential consequences from the initiation of the explosives within a facility is essential. Currently, there is a reasonable understanding of the effects of blast in such circumstances but significantly less knowledge exists on the effects of weapon fragments and building debris (hereafter referred to simply as debris).

The effects of debris on personnel and property are dependent on their mass, velocity, shape and number. The characteristics of primary fragmentation from the explosion source may be determined by calculation using the Gurney equations or their equivalent [8-11]. Corresponding methods are available for the estimation of secondary fragmentation from structures [12, 13]. However, these methods do not determine the interaction of that fragmentation with the containing structure. Debris from the containing structure is generated and projected by the interaction of both the explosion products, i.e. shock and quasi-static pressure, and the primary fragmentation with the elements of the structure. Thus, the fragment and debris cloud that is projected into the field around the explosion site is complex and not readily calculable. In practice, therefore, it has been and will continue to be necessary to perform testing in order to quantify these effects. Additional data also are gathered from the analysis of accidents. In all cases, a consistent approach for the collection and analysis of such long been the information is needed.

Clearly, in the deduction of data from accidental events, the information to be gained is only that available after the fact. The majority of this information will be descriptors of location (range and bearing), weight, and nature. Some secondary evidence may be available to provide estimates of debris velocity, for example the depth of penetration in trees, soil or other materials. However, in the planned experiment, provisions may be made for more extensive, detailed and controlled measurements. An additional and important aspect of the planning process must be the representation of credible and/or worst case accident scenarios.

Of the utmost importance in the gathering of data, be it from accident or planned experiment, is the need for consistency in its definitions and format. Many of today's problems in the analysis of historical explosion effects data lie in the incompatibility or inconsistency thereof. This need for consistency in the gathering of the data must be extended to its analysis. Whilst interpretation is not considered in this paper, it can be argued that consistency should also be extended to this. In the paragraphs below an attempt is made to provide a framework for this consistency of approach.

3. OBJECTIVES

Based on the consequence information obtained after an accident or planned test, probabilistic risk assessments may be carried out, deterministic safety distances deduced or predictive models developed. In all cases, a knowledge of the spatial and energy distributions of the debris is necessary. Whilst in an ideal world, a detailed description of the debris field in terms of mass versus velocity versus number density is needed as a function of distance from the explosion source, this is not totally achievable in practice. What is achievable is the measurement of mass versus debris number versus range or position and an estimate of the distribution of initial velocities. The prediction of velocity-time histories of individual debris pieces is, at best, conjectural due to the indeterminacy of initial velocity, randomness of shape (drag) and the effects of ricochet, roll and bounce. The objective, therefore, must be to achieve the best information, approaching the ideal, to describe the debris field.

4. PLANNED EVENTS

4.1 PRE-TEST PREPARATION

Careful preparation and planning for any test is essential to the successful achievement of its objectives. Every aspect of the test plan and its translation into practice must be considered in the light of the test objectives and their optimal satisfaction. So far as is possible, models, where available, should be used to predict maximum debris throw, directionality, velocity and debris dimension(s) as all will play a part in influencing the measurement techniques to be used and the test preparation needed. Typical software for this purpose includes DISPRE[13], DISPRE2[14], TRAJ[15], and various finite difference codes. Empirically based models to predict ricochet and roll are also under development

4.1.a The Test Range

It is important that the test range should be sufficient in size and condition to meet the needs of the test. Ideally, the area to be used for the test should be flat over a circle, centered on the test structure and have a radius at least 130% of the predicted maximum throw of the debris; the additional 30% in range being an allowance for underestimation of the maximum debris throw. Where range space is limited in some directions, careful orientation of the test structure can be used to reduce the space required. In many circumstances, little or no wall debris is projected along the directions of the diagonals--the debris scatter pattern being quatrefoil in shape. However, it must be born in mind that, if the structure has a concrete roof and/or strengthened corners, there may be a diagonal contribution from these. In smaller test arenas, it may be necessary to limit the directions in which debris effects can be measured; it is, however, important that in those directions there is sufficient range to assure uninterrupted debris throw -- again 130% of the predicted maximum debris throw is suggested.

While it is difficult to advise absolutely on the flatness of the test area, it is clear that sloping ground will enhance the debris ranges down hill and reduce them uphill. It will also lead to skewing of the debris distributions in the cross-slope directions. In order to minimize these effects, it is recommended that ground slope should be less than 1% over the test area. Again some alleviation may be gained by careful control of test orientation on sites where there are local slope variations.

Inevitably, the test site will be strewn with stones, natural rubble, lumps and hollows. The degree to which these should be cleared, flattened or filled is dependent on the test and the predicted debris characteristics. As a rule, only clusters of large boulders that might significantly distort the debris throw (including roll and bounce phases) should be moved. In a similar vein, only holes or lumps with the same potential should be filled.

There may be a carpet of vegetation over all or part of the test area. This should not be so dense as to impede the scatter of debris or reduce the efficiency of the post-test debris search phase. The degree to which the test area should be cleared will, for example, also be dependent upon the type of debris location to be used. The amount of clearing will be greater if aerial photography is to be used rather than personnel search on foot.

It is the authors’ experience that early communication with the environmental and/or conservation authorities responsible for the test area is vital to reduce or avoid conflict where there is a need to clear or modify the topology of the test site. Such conflict, if it is allowed to occur, could delay or jeopardize the trial.

The test site will, in all probability, have been used for testing before and will be scattered with old debris. It is essential that there should be no confusion between old debris and that being generated in the planned test. If there is any chance of confusion, the old materials should be cleared. If clearance is not practical, an alternative may be to mark them with spray paint.

It is important that the test site surface is firm enough that debris or fragments landing on it are not lost, i.e., buried in sand or submerged in mud or water. In addition to a consideration of the geology or geography of the area, meteorological factors, e.g. rain or wind will have an effect on the test site and may have to be taken into account and test schedules altered as necessary.

4.1.b The Test Structure

The test structure clearly has to be representative**,** in terms of building codes and standards, of existing or planned buildings. However, much can be done in the detailed design to improve or extend the debris information gathered. The requirements of risk analysis or safety distance determination can generally be met with a knowledge of the total debris field from the whole structure and its contents. However, when it comes to the development of predictive models, there is a need to identify the source of the individual debris--wall or roof, structure contents, etc. For all concrete buildings, this may be accomplished by simply dying the roof material a different color to the walls. If the information demands are greater, then paint can be used to color different parts of walls and roof. In those areas that would be exposed to high temperatures, a paint that is resistant to the effects of such temperatures must be used. The patterns to be used can be based on the predicted shock load contours. Bright colors can also be a simple aid to the efficient location of debris after the event. When selecting a color scheme, care must be taken to select colors that do not blend with the surrounding terrain and vegetation. It is the authors’ opinion that the incorporation of this type of measure (color coding of potential debris), which maximizes information retrieval and costs little (in terms of the full test cost), is worth doing even if it goes beyond the immediate aims of the experiment.

Orientation of the test structure on the test arena has already been mentioned. Of importance, when data retrieval is limited to one or two structural aspects by the arena, is the choice of test orientation. Normally, an orientation would be chosen from the predicted worse case direction unless, for example, specific novel designs were being tested.

Consideration must be given to the choice of ancillary equipment and fixtures to be included in or on the structure. The simple question to ask for each item is: Does its exclusion detract significantly from the debris to be generated or will its absence affect the generation of the debris?

If the answer is “no," then its inclusion in the structure is unnecessary. An example might be a personnel door. While it would only contribute a few fragments, its absence would affect the response of the structure in that there would be an open vent and the pressure regime and, hence, the debris generation would be changed. Thus, the decision must be to include the door. An example of a possible exception is the inclusion of lightning conductors. They would not affect or add materially to the debris. However, if there is any intention to store explosives in the structure on a temporary basis prior to the test or if the trials authority considers it necessary for the test, then they must be included.

4.1.c The Explosives

The explosives must be assembled and stowed in the structure in accordance with the current regulations, e.g., the relevant parts of Reference 1 or 16.

The means of initiation of the explosives must be in accord with the aims of the test and to an acceptable standard. If the test is intended to simulate an accidental fire environment, then a fire meeting the requirements of the UN Test 6c [17] must be arranged. Examples of this are the Hazard Division 1.2 tests in igloos carried out in 1993 and 1995 [6,18]. Hazard Division 1.1, mass explosion tests, will require multi-point initiation throughout the stack to ensure complete detonation. One method of achieving this is to use multiple detonators and detonating cord. Typically, on a large stack of MK 82 bombs stored on 6-bomb pallets, one bomb per pallet would be primed and initiated. Other items might require additional priming.

4.1.d Meteorological Limits

Mention has already been made above of the need to avoid periods of rain where the test site might become unacceptably muddy or flooded. In some places (Woomera, South Australia, for example) prolonged periods of dry weather can bring their own problems. The dust clouds generated by the expanding blast wave can occlude the fields of view of video or cine cameras, thus reducing their data collection capability. This is difficult to combat. Thorough wetting of the area around the structure with water or petroleum-based products does little to ameliorate matters. Wind will, of course, exacerbate the dust problem. In addition, wind will also apply bias to the debris distribution, particularly in the far field where times of flight are long (seconds). As a broad guide, a displacement of 0.5m can be expected for each knot of wind and each second of travel. It is recommended that testing should not take place in wind strengths greater than 10 knots.

4.1.e Site Survey

The requirements for a survey of the site are as follows:

1. Location of cameras, scaling screens/poles and instrumentation
2. Location and orientation of the structure
3. Debris search and location

To optimize the quality of the data generated from the analysis of video/cine records, it is essential to determine the positions of the cameras and their scaling screens and/or poles relative to a fixed datum.

Except for documentary cameras, all camera axes should be either in the plane of the normals to the structure walls or perpendicular to them. Therefore, it is essential to locate the position of the structure relative to the fixed datum and define the perpendicular bisectors of the four walls.

The survey requirements for debris search and location will be highly dependent on the scale of the test and the planned debris data recording method. Recording methods fall into two categories:

1. By location within azimuthally and radially defined zones.
2. By individual debris piece location and mapping.

If debris is to be collected within pre-defined zonal areas, these areas have to be surveyed in prior to the test. They will normally be defined as elements of a radial coordinate system, the origin of which will be at the center point of the structure and the originating axis will be related to the perpendicular bisector of one wall. Radials should be marked at the desired angular intervals. The authors have found that 10° is suitable in most cases; however, allowance should be made for further sub-division after the event where it is clear that the angular debris density variation is large within the pre-defined interval. Also of importance is the exact choice of the originating axis position. If it is along the normal to the structure wall, then the debris density peak may be within 10° either side of the normal, i.e., within a 20° band, whereas if the originating axis is taken at + or - 5° from the normal, then the majority of the density peak will be contained within one 10° zone. Post-trial sub division of the angular division can offer the opportunity to examine both options.

Having set the angular radials, each must be marked at intervals to define the individual search areas. The interval distances will be a function of the scale of the test and the predicted maximum debris throw distance coupled with the practical limitations of carrying out the debris search. The grid should be marked out to 1.3 times the maximum predicted debris throw. In tests carried out by the authors, zone lengths of 20 m have been used where the maximum debris throw has been around 300 meters; for predicted debris throws of 2000-3000 meters, a 100-meter zone length is proposed. As with the angular incrementation, allowance should be made for post test sub-division if the debris density distribution demands it.

If a post-test survey technique is to be used to locate each individual debris piece, there will be no need for the above. However, it is recommended that a Cartesian grid is surveyed in over the test site to assist in the management of the search operation. The size of the grid will be dependent on the planned search technique. If personnel are to be used to search the area, then the grid size will be proportional to the number of personnel to be used. If vehicular search is to be used, it may be possible to increase the grid size; however, any decision to do so must take into account the ground conditions (vegetation cover, etc.) and the abilities of the search team. The origin and orientation of the grid is not of great importance but is probably best tied to the normals to the walls of the structure.

All surveyed points should be located to an accuracy no worse than 0.1° in azimuth and 0.1% in linear dimension (minimum 0.1 m).

4.1.f Documentation

Prior to the test, all data sheets for use in post-test recording should be designed and agreed. Examples for manual recording of zonal data are shown in Figure 1 and for individual debris locations in Figure 2. In Figure 1, the multiple data sets within each zone can be used to represent subsets of the total zonal information. Further, if there is more information than can be contained in one zonal block of the form, additional blocks may be used to characterize a single zone. Moreover, if data is to be entered direct to spread sheets, then the spread sheet format and data categorization (e.g., debris type identifiers) must be agreed. Generic debris descriptors are presented in Table 1. It is recommended that these descriptors be used for all debris collection. Additional event or site specific descriptors as well as other more detailed descriptors can also be used. However, these must be well defined and each must be a sub-set of the generic descriptors. A sample spreadsheet is shown in Figure 3.

Of equal importance is the documentation of the search management process. This extends from the test manager's search control techniques to the labeling of individual debris (either singly or collectively dependent on the technique used). It is essential that the search is carried out methodically with a high confidence in its completeness.

It is essential that all aspects of the setup of the test, the test structure and the explosive charge are recorded using still photography and video or cine. Of particular importance are views of the test structure (internal and external) and details of the energetic materials. It is better to discard excess records after the event than to regret not having them. Particularly when there are multiple tests, it is important to include in each picture/video sequence an indication of the event number, date, etc. Photographs in particular get displaced from their original locations and then one piece of structure or test site looks much the same as others.

All details of the test explosives, such as dimensions, weights, lot numbers, origins, history, stock numbers, etc. must be recorded. Details of camera and instrumentation locations, calibrations, fields of view, frame rates, etc. must be logged. If these are changed during the course of the testing, the changes must also be recorded.

A test diary/log must be maintained. This will provide chronological notes of all actions, observations, and decisions made on the test site and again forms an essential part of the test record.

4.1.g Video/Cine and Instrumentation

A coordinated instrumentation plan must be produced and agreed upon before the event. The positions, as well as theoretical fields of view of all cameras and their associated calibration screens/poles will be needed in advance for survey purposes. However, it will be almost inevitable that local site conditions, etc. will dictate changes; prior to each test, all fields of view, as set up, must be agreed upon and documented.

The choice of video or cine is very much left to the test director. For this type of test, there is no real need for very high speed recording. While it is accepted that cine offers the best resolution, state-of-the-art high speed or normal video offers good resolution with the advantage of immediate play-back and is preferred by the authors, particularly on multiple event tests. The ability to make changes to fields of view, exposure, etc. without the need to await film developing (which often cannot be done on or near remote test sites) adds greatly to the efficient management of the test.

Experience has shown the importance of having a common timebase across all instrumentation including cameras. A continuously running timebase will be acceptable so long as Time Zero (the time of initiation of the charge) is recorded such that it may be superimposed on all other records.

The measurement of the initial velocity distribution of structural debris is the area in which improvements and alternative means are sought. Data to date have been sparse and of low reliability and accuracy. In addition to the video/cine recording of debris, attempts have been made to determine initial velocities of structural debris using Doppler Radar [19]. These have shown some promise, though there is more technique development necessary. There is much room for innovative thinking in this area to improve the ability to measure this important parameter.

TEST NUMBER: ____________

ZONE		ZONE	
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
ZONE		ZONE	
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
ZONE		ZONE	
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
ZONE		ZONE	
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________
WEIGHT ________	WEIGHT ________	WEIGHT ________	WEIGHT ________
TARE ________	TARE ________	TARE ________	TARE ________
TOTAL ________	TOTAL ________	TOTAL ________	TOTAL ________
COUNT ________	COUNT ________	COUNT ________	COUNT ________

FIGURE 1. FIELD DATA SHEET FOR ZONAL RECOVERY

TRIAL NUMBER: ____________ SHEET NUMBER:

FIRING NUMBER: ____________

ZONE NUMBER: ____________

FRAGMENT TYPE	FRAGMENT MASS (kg)	DIM 1 (mm)	DIM 2 (mm)	DIM 3 (mm)	COMMENTS

FRAGMENT TYPES

B=brick
C=concrete
D=door
E=energetic material
F=miscellaneous steel
M=miscellaneous other metals
O=intact ordnance item
P=case material from donor (primary fragment)
R=rebar
S=non case material from donor

FIGURE 2. FIELD DATA SHEET FOR INDIVIDUAL COLLECTION

CODE	DESCRIPTOR
B	Brick
C	Concrete
D	Door
E	Energetic material
F	Miscellaneous steel
G	Mortar/cement
H	Structural appurtenances (hardware)
M	Miscellaneous other metals
O	Intact ordnance item
P	Case material from donor (primary fragment)
R	Rebar
S	Material from donor--non-case material (secondary fragment)
U	Other

TABLE 1. GENERIC DESCRIPTORS FOR USE IN DEBRIS DESCRIPTION

FRAGMENT NUMBER	RANGE (meters)	BEARING (degrees)	WEIGHT (grams)	OPTIONAL			DESCRIPTOR			COMMENTS
				DIMENSION 1 (mm)	DIMENSION 2 (mm)	DIMENSION 3 (mm)	PRIMARY	SECONDARY	TERTIARY	

FIGURE 3. PROPOSED SPREADSHEET FORMAT FOR DEBRIS COLLECTION

4.2 POST- EVENT DATA COLLECTION

Post-event data collection involves three processes:

1. Finding each debris piece,
2. Determining the location, weight, and description of each piece, and
3. Cataloging of the information associated with each piece.

An examination of the recovery area post-event will, generally, show that within some, to be defined, distance from ground zero, the number of debris pieces becomes so high that it is impractical to count or catalog individual bits. This region is known as the debris saturation zone. Within this area, all debris pieces should be collected and their aggregate weight measured or estimated.

The collection methodology that is ultimately used will be selected on the basis of the pre-event planning process and an assessment of the on-site conditions present post-event. Under ideal conditions and with unlimited resources, the location, weight, and description of every debris piece would be noted and recorded. This is not always practical. Under more realistic conditions, two techniques with minor variations predominate. The first uses pre-determined and pre-event prepared, fixed recovery zones (see discussion above). The second involves identifying pre-selected pieces, then determining their location, weight, and description. This selection process may be as simple as choosing all material ejected in preferred directions. It could also be as complete as selecting and cataloging all debris located beyond the edge of the debris saturation zone.

In all cases, however, the first step is the location of each debris piece. This process will usually involve a search by personnel who are either on foot or in vehicles. Because of the chance of missing or not locating items, vehicular search is only appropriate when debris may have been thrown more than, say, one kilometer. When this is thought to have occurred, it is better to use vehicles to transport personnel and equipment to the search area and then conduct the actual search on foot.

In addition to debris location, a thorough examination of the recovery area can produce other useful information. If a fragment has penetrated into other materials, an estimate can often be made of its impact velocity. Likewise, when debris impacts other objects or structures (trees, buildings, etc.) and leave marks indicating the point of impact, information such as trajectory directions can also be deduced. For example, if after an accident, a metal fragment is found embedded in the trunk of a tree, the depth of penetration can be related to its impact velocity and its position relative to the explosion site gives an indication of its direction of throw. Subsequent controlled experiments may, of course, be needed to quantify its speed.

4.2.a Collection By Zone

In this approach, collection zones will have been defined and their boundaries located prior to the start of data collection. Each zone is searched by a recovery team. The number of personnel required for this operation will be determined by the size of the recovery zones and the amount of time allocated for the operation. One person can adequately search an area that extends approximately 3 meters to either side of his/her location; however, for effective, 100% pickup in high debris density zones, this may be reduced to as little as one meter. Sometimes, more than one pass through a zone will be required in order to completely cover the area.

During the search, each debris piece located within the zone is identified, picked up, and transported either to a central collection area (usually one corner of the zone) or to a central sorting area away from the grid. The number of pieces recovered within the zone and their description(s) are noted and recorded. There are two options for the determination of the weight. The first is to use a portable scale and weigh/record the weights in the field. The second is to package the pieces from each zone with appropriate identification and then collect and remove all this material back to the central sorting area. At this location, each package is opened, the numbers and description(s) of the items verified, and each piece is weighed. This weight must be associated with a unique fragment/debris identifier so that the location of the piece and its description can be associated with the weight. It should be emphasized that all large debris should be photographed in situ with a scale reference in the field of view before they are moved or disturbed.

One variation on this method is the use of collection pans or debris traps. These are areas or structures of known dimension that are placed at selected locations around the test area. Because their dimensions are known, these provide point estimates of the debris density at that location. If enough of these traps are placed around the test area, then these point estimates can be used to estimate the total debris distribution. This method has the advantage that it appears inexpensive and easy to apply. In practice, however, this is usually not the case. In order to adequately sample the debris distribution, large numbers of collection boxes are required. Further, in some situations, the debris density is changing rapidly with range and/or azimuth; such changes may be missed or inadequately represented by a simple sampling technique. An additional problem with using this type of technique is that the pan or trap may interfere and modify the debris cloud and thus give incorrect information

4.2.b Individual Location

Once it has been decided that the location and description of each piece will be obtained, there are several options that can be used to achieve the location portion of this goal. These include, but are not limited to, compass and tape, conventional surveying techniques, computerized survey techniques including use of a laser range finder [20], the use of special binoculars that have a built in range finder and compass [21] and Global Positioning System (GPS) or Differential GPS (DGPS) receivers. The use of GPS/DGPS for this purpose is still under development. As far as the authors have been able to ascertain, its use on an actual data recovery has been discussed, but not implemented. Each of these techniques has its strengths and weaknesses and each may not be appropriate for all situations.

If there is a relatively small amount of debris and this material is located close to ground zero, then a compass and tape approach could be appropriate. In its simplest form, the tape is used to measure the range of each piece from ground zero. The compass is used to estimate its bearing, also with respect to ground zero. While simple and easy to use in concept, this method has the highest potential for error--especially in the estimation of the bearing.

Conventional survey techniques are always appropriate. Their main disadvantage is the amount of time required to complete each measurement. If there are large numbers of debris pieces involved, the amount of time required to conduct the survey may become prohibitive. This disadvantage is essentially eliminated if a computerized survey system with a laser range finder is utilized. With this system and a small crew (less than eight), one-to-two thousand points can be surveyed in an average day. However, in terms of total data retrieval, this efficiency will be reduced as debris weight and description information are included against each item. With this computerized system, the information is automatically stored in computer memory, eliminating the potential error source that would be introduced by manual transcription.

For those situations where there are too many pieces to use the compass and tape method and not enough to justify the use of a full, computerized survey, special binoculars might be used. These specialized instruments have a built in range finder and compass. They can be used, therefore, to measure the range and bearing of each piece with respect to ground zero. A disadvantage with this technique is that the information must be recorded by hand or by direct transcription into a computer, though some models are equipped with a computer interface. When the binoculars are linked directly with the computer, transcription errors will be eliminated.

All of these techniques work best where there is line of sight between the debris piece and ground zero. If there is no direct line of sight, intermediate survey points must be established-- introducing the potential for additional errors.

A relatively new technique involves the use of GPS receivers. However, the best positional accuracy that can be achieved with these devices is about $\pm$ 3 meters (DGPS can provide accuracies of 3-5 cm, with very expensive systems providing accuracies of 1 cm). This 3-meter accuracy may not be adequate at the closer ranges; however at ranges greater that 500 meters, it is sufficient. Thus the use of GPS/DGPS appears to be best suited as a method to augment one of the survey techniques described above.

4.2.c Aerial Photography

There exists another technique which can be used as a backup to any of the methods discussed above--aerial mapping/photogrammetry. As was demonstrated after the DISTANT RUNNER Event [22,23], conventional aerial photography and stereo photogrammetry techniques can be used to generate position information and size estimates for any debris piece whose size is resolvable in the photograph. The use of such an independent method is doubly useful. First, it serves as a check on the results obtained by the other methods and, second, it can be used to identify/locate any debris that may have been missed on the initial survey. One limitation to this technique may be its ability to provide adequate debris identification.

4.2.d Fragment/Debris Weight

As has been previously indicated, the weight of each debris piece is required. In most situations, this will be determined by weighing the individual pieces. However, in those situations where the piece is too large to weigh easily, its maximum dimensions (length, width, and height) and its weight should be estimated. Weighing later on a weigh bridge (truck scales) has also been used.

For all other pieces, the resolution of the scales that are used should be better than 1% of the total weight of the item. The maximum resolution that could be required is 1 gram. There are commercially available, portable, battery-operated scales with the required resolution, often with a computer interface.

An alternative approach that is applicable in some situations is the sorting of debris by dimension rather than weight. Dimensions would be chosen to represent selected weight bands for specific materials.

5. ACCIDENTS

The analysis of the debris produced by explosion accidents generally proceeds in a similar manner to that described above for planned events. However, because it is an unplanned event, none of the pre-event planning, previously described, can be performed.

Generally, for accident situations, the location, weight, and description of every debris piece should be noted and recorded. In addition, the generic descriptors used in test situations should be expanded to be more descriptive of each item. Because of the nature of the event, the interest in the results is more than scientific. For this reason, every debris piece should be photographed. Included on each photograph should be a unique identification number that ties the photograph to an entry in a debris description catalog. Also, each photograph should contain an in-focus scale referent. Because of size, shape, or special features some debris may require more than one photograph. Debris must be retained until the completion of all accident investigations and litigations.

The choice of an appropriate collection methodology will depend upon an on-site assessment of the situation. Because it is an accident and not a planned event, the terrain around ground zero may not be flat or level. There may be hills, valleys, vegetation, barricades or other structures in locations that could influence the debris cloud. For this reason, a topographic map of the area that gives the locations of such items must be included with the debris catalog. The map should extend out to a range to include the farthest piece of debris. The contour scale of the map should be chosen such that all prominent terrain features in the vicinity can be resolved.

As above, aerial photography and mapping is useful in locating debris pieces and in being able to assess the symmetry of the debris field.

6. DEBRIS PICK-UP DATA ANALYSIS

The main aim of the analysis of the pickup data from tests or accident investigations is the generation of debris mass and number distributions and their defining functions. According to the test or accident investigation circumstances, the degree to which this aim can be fulfilled will vary. The shear amount of debris may preclude more than a few sampled mass distributions or the zonal dimensions used in a test may conceal some detail of the spatial distribution. For example, in tests in Australia [19] in which the debris distributions from explosions in small buildings were determined, most of the debris was sorted to discard material which had no dimension greater than 50 mm (deemed to be equivalent to an object with a weight of 100 grams). The remainder were simply counted. Only in two, orthogonal, 10° rays was a full mass analysis carried out. Mass distributions as a function of range were produced in those directions. To do more would have been prohibitively time consuming.

The data that is gathered is simply the position or zone at or in which the debris piece was found, i.e., the point at which it came to rest. To arrive at that point, following its initial acceleration, it will have followed a ballistic trajectory defined by its velocity, mass and dimensions (drag coefficient) to its first point of impact. Upon impact, it may have buried itself, bounced, ricocheted or rolled. Dependent on which occurred, further ballistic, burial, bounce, ricochet and roll phases may have followed. At any point, this passage may have been perturbed by in-flight collision with other pieces of debris. Furthermore, at any impact point the piece of debris may break up and thus what we find at the pick-up point is only a part of something which was larger as it traveled over most of its journey. As a result of all this, consideration of the debris data, in its “as collected” form and in terms of measuring its potential damaging interaction with personnel or materiel targets must be considered as conservative for the following reasons:

a. Over the final stages of its passage from the explosion site to pick-up point, any piece of debris will be low in energy and thus not harmful.

b. Over parts of its trajectory, a piece of debris may be so high above the ground as to have no chance of hitting anything, except, perhaps a bird or airplane.

c. The piece of debris may be so low in mass as to be non-injurious.

However, for many years this conservatism was accepted and all debris analysis was performed on the data as collected in its incremental form. In recent times, consciousness of the non-realistic treatment of the data coupled with a drive, for economic reasons, to control or minimize the degree of conservatism in consequence analyses has led to a re-examination of the methodology.

Looking simplistically at a storage structure, most projected debris originates from two sources--the walls and the roof. Roof debris is mostly projected over a small angle about the normal to the ground and, hence, rises high into the air and returns to earth at a high, nearly vertical, angle. As a result, it will only have a consequence at or near where it lands. It can, therefore, quite justifiably, be treated by the old incremental analysis methods described below.

Debris from the walls is, in general, projected over a small angle about the normal to the walls, i.e., nearly parallel to the ground. As it leaves the explosion site, it sweeps across the ground at a relatively low altitude and may, therefore, interact with any target, personnel or structures, as it passes. It is essential, therefore, that the contribution to consequence of wall debris be integrated over its full path length. A method that accomplishes this, called Pseudo-Trajectory Normal (PTN) Analysis, is described below.

As might be expected, in practice the picture is not so simple. Debris pieces will be projected at intermediate launch angles and will only contribute over parts of the passage to their final location or debris from roof and walls may not be separable and thus cannot be treated separately. A method of analysis, a hybrid of the foregoing, which addresses this problem is being developed. An indication of the approach being taken is described in the paragraphs on Composite Debris Analysis.

The requirement for a full debris mass analysis is dependent upon the end use of the data. For risk assessment and safety distance determinations, it may not be necessary. However, for model development, it may be essential. Whether or not full debris mass analysis is carried out, the numbers of debris with low mass can be removed from the analysis. The choice of a limit below which the debris is to be considered non-lethal or non-damaging is critical. Limits that should be applied are discussed along with their derivation in the paragraphs on Debris Mass Analysis.

6.1 <u>Incremental and Continuum Analysis</u>

The positional debris information, whether collected zonally or individually, is sorted and sub divided into fixed polar zone populations, $N_{r\theta}$, where r_c is the radius and θ the polar angle to the center of the zone (in degrees). The radius of the start of the zone is r and the incremental length of the zone is Δr. The debris density for that zone is then given by one of two formulae, depending upon how r is defined:

$$D_{r\theta} = 360N_{r\theta}/[(\pi\Delta r\,\Delta\theta)(2r+\Delta r)] \quad (1)$$

$$D_{r\theta} = 180N_{r\theta}/\,(\pi r_c \Delta r\ \Delta\theta) \quad (2)$$

where $D_{r\theta}$ is the zonal debris density and $\Delta\theta$ the zone angular increment in degrees. Fragment/debris density distributions as a function of range and polar angle can then be plotted. An example of such data plots is shown at Figure 4 [19].

In 1994, as a method of improving the statistics associated with the debris analysis procedures and to correct problems that had been exposed in the fixed grid methodology, Jacobs and Jenus [24] proposed a new methodology for analyzing these debris distributions. Their algorithm utilizes a moving grid, using a procedure similar to that for calculating a sliding average. In this procedure, the analyst examines the radius-azimuth data and selects realistic bounds (minimum and maximum angles and distances) for analysis. Once a starting point is selected, a value for a sector of an annulus to be used as the "electronic debris collection pad" is also chosen. The methodology calculates the area of this pad, counts the number of fragments on that pad and then calculates the fragment density at that point using equations 1 or 2. It then creates another sector of an annulus of the same width, some increment further away from ground zero and calculates the debris density for that sector. It continues in this manner until the leading edge of the sector of the annulus includes the last fragment to be considered. As before, the coordinates of the sector are those of the center point of the annulus.

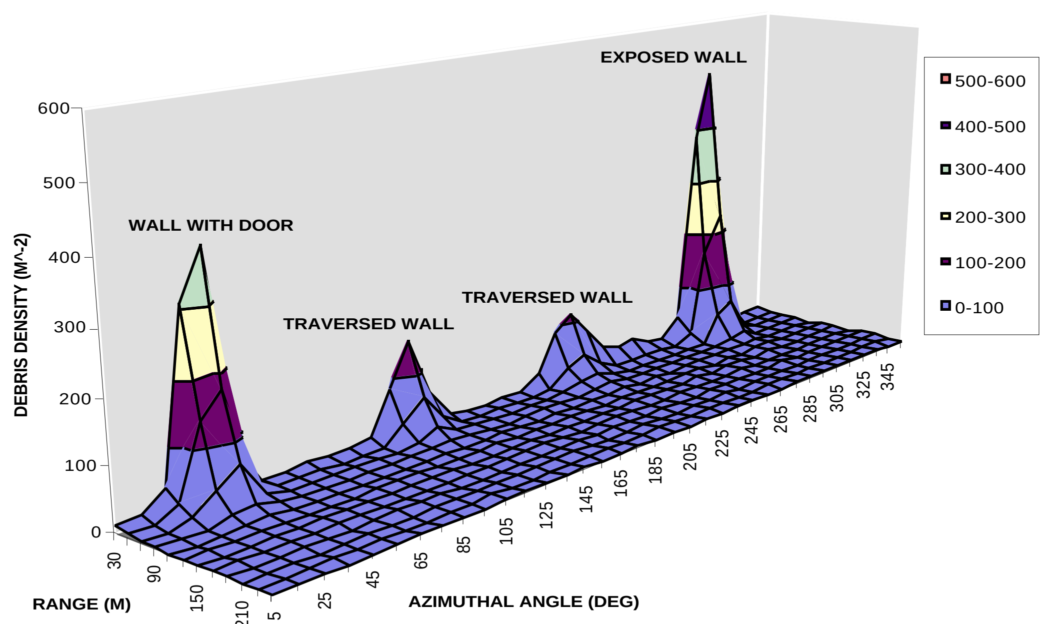

FIGURE 4. DEBRIS DENSITY VARIATION WITH AZIMUTHAL ANGLE AND RANGE FOR A SMALL BRICK BUILDING

6.2 Pseudo Trajectory Normal Density

In 1990, the Secretariat of the DDESB recommended that all debris densities should be measured as trajectory-normal, i.e., a density measured in a plane perpendicular to the trajectory at any point. This is difficult, if not impossible, to determine experimentally. Ground surface collection data, on the other hand, are straight-forward to obtain. In order to approximate “trajectory normal” densities, it was proposed that a “pseudo-trajectory normal” (PTN) density be defined. At a given location, this density would be computed by defining the number of debris pieces to be considered as all appropriate debris material at that location plus all material that had to pass through that location to reach a greater range. One of the following two formulae can be used to compute these densities:

$$PTN_{r\theta}(i) = [360/(\pi\,\Delta r \Delta\theta \{2r + \Delta r\})] \sum_{i}^{i\max} N_{r\theta}(i) \tag{3}$$

$$PTN_{r\theta}(i) = [180/(\pi\, r_c \Delta\theta \Delta r)] \sum_{i}^{i\max} N_{r\theta}(i) \tag{4}$$

where $PTN_{r\theta}$ (i) is the pseudo-trajectory normal (PTN) zonal debris density for the i-th zone, r, r_c, and θ are defined as above and imax is the number of the zone that contains the furthest fragment. A more detailed discussion of trajectory normal and pseudo trajectory normal distributions and their computation is presented in Reference 25.

6.3 Composite or Modified Pseudo Trajectory Normal Density

As discussed above, the process of computing pseudo-trajectory normal densities may be quite conservative, since many pieces are thrown well above a zone and, hence, would not interact with persons in that zone. In order to make more realistic estimate of the true trajectory normal density, the DDESB tasked one of the authors to re-examine the PTN algorithm and recommend updates or modifications. The results of this study will be described in detail in Reference 26, but may be summarized as follows. Instead of considering all debris passing through a zone as contributing to the density in that zone, calculations indicate that only 1/3 of such debris contribute. It should be noted that this nominal value of 1/3 encompasses nearly all of the data. Therefore, a Modified Pseudo Trajectory Normal (MPTN) density should be defined and used. This is defined for a particular location by considering all appropriate debris material at that location plus all 1/3 of all material that had to pass through that point to reach a greater range. The factor of 1/3 accounts for the different trajectory paths--high angle versus low angle. The appropriate modifications to equations (3) and (4) are shown below:

$$MPTN_{r\theta}(i) = [360/(\pi\, \Delta r \Delta\theta\{2r + \Delta r\})][N_{r\theta}(i) + (1/3) \sum_{i}^{\text{imax-1}} N_{r\theta}(i+1)] \tag{5}$$

$$MPTN_{r\theta}(i) = [180/(\pi\, r_c \Delta\theta \Delta r)][N_{r\theta}(i) + (1/3) \sum_{i}^{i\max-1} N_{r\theta}(i+1)] \tag{6}$$

The authors propose, therefore, that the Jacobs-Jenus methodology be combined with the modified pseudo-trajectory normal model, and be used, where practical, in all future debris analyses to generate debris densities as a function of range. It should be noted however that this methodology may cause the debris density/range curve to become non-monotonic and cross the IBD density on multiple occasions. This is due to the introduction of incremental values into the continuum accumulative distribution. In this circumstance it is suggested that the crossing at the furthest (greatest) distance be used.

6.4 Debris Mass Analysis

If full debris mass data have been collected, they should be sorted, most certainly, by polar angle and preferably by polar zone. If the angular increment has not been preselected, it should be chosen with regard to the rate at which the debris pattern changes with angle. If, for example, the mass distribution in one lobe of a quatrefoil spatial distribution is required, then the polar angular increment should be chosen to encompass the whole lobe. If the mass distribution is to be examined as a function of angle then an incremental width should be chosen which is sufficiently small that it will not mask changes in distribution with angle.

It is recommended that mass bands should be in the logarithmic sequence 1,2,5,10, etc. commencing at 10 grams. This is of benefit if, for example, the goodness of fit to a Mott [27-31] or Porzel [30] relationship is to be examined. It is suggested that, at the upper end of the distribution, the summed frequency of all debris greater than 10 kilograms is recorded. A typical set of mass distributions [19] for different ranges is shown in Figure 5.

Either pre-test, post-test or at the data analysis stage a decision may be made to limit the mass data collection or analysis. Very small debris will not be injurious, particularly at long ranges. Internationally, it has been the custom and practice to consider a debris energy of 79 Joules (58 ft-lbs) as the threshold for potential fatal effects. This criteria had its origins in Napoleonic times [31-33] but much more recently [34] has been shown to adequately envelope the many more sophisticated debris mass/velocity/fatality models that have been developed.

From the limited database of information on the velocity of debris produced by explosions, a typical debris velocity outside the immediate vicinity of the explosion site is of the order of 40 meters/second. Given the 79 Joule threshold and using the 0.5 mv^2 energy equation for kinetic energy, the minimum mass to achieve the threshold energy is approximately 100 grams. It should be noted that this argument quite clearly excludes primary fragments from detonating ordnance. This is not considered to be a problem as, in most cases, the more massive debris from structures are thrown to greater distances than small detonation fragments and the greatest interest from the safety community's point of view is in far field effects. It is, therefore recommended that, if mass data distributions are to be restricted, then the lower limit should be 100 grams.

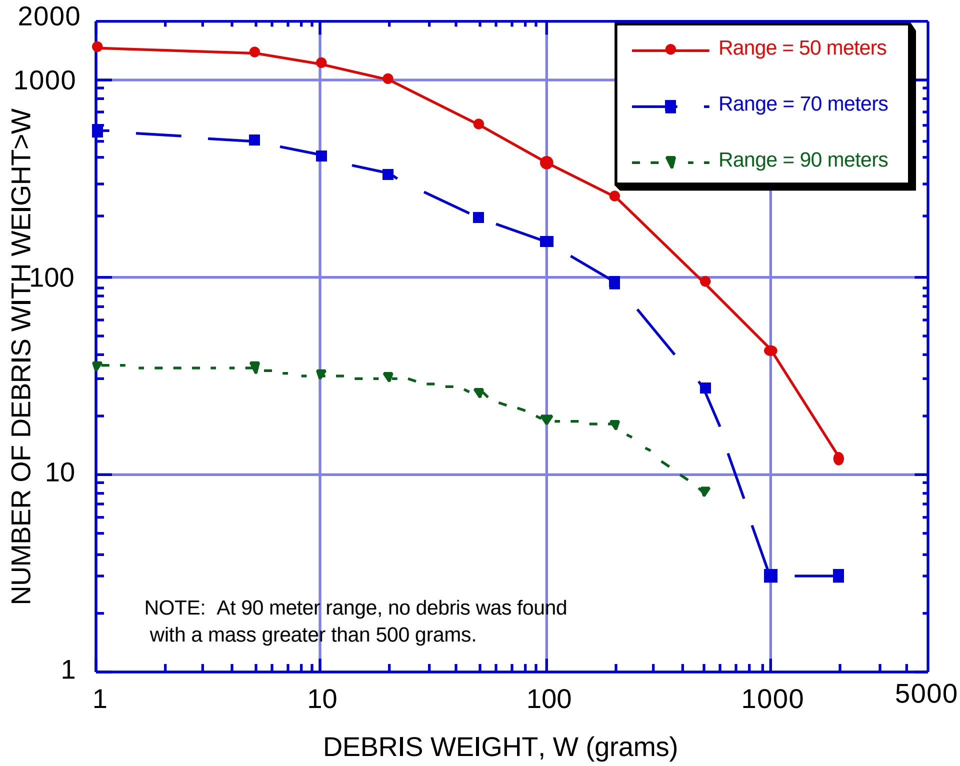

FIGURE 5. TYPICAL DEBRIS DISTRIBUTION FOR DIFFERENT RANGES FOR A SMALL BRICK BUILDING

6.5 Debris Initial Velocity Estimates

After the debris have been collected and their weights determined, questions are often raised about their initial velocities. For the planned event, these questions may be answered by the optical and/or radar instrumentation. What about the unplanned event or the situation where an independent estimate of velocity is required? The following methodology can be used to make a crude estimate of the launch velocity, based upon three pieces of information, of debris projected into the far field. These pieces of information are: (1) the final range of the debris piece, (2) the weight and size of the debris piece, and (3) the type of debris.

This methodology ignores ricochet and roll and assumes that they do not occur; i.e., the final impact point of each debris piece can be calculated by a purely ballistic trajectory (Note: The trajectories that are computed assume the debris is launched at its optimum launch angle--maximizing range for the given launch velocity). The method further assumes that individual debris pieces do not shed mass over the course of the trajectory or break up upon impact. It also assumes that the debris pieces can be represented as compact, “chunky shapes, rather than long rods or spheres. Strictly speaking, this methodology applies only to far-field debris.

To date, the methodology has been established for steel and concrete debris. The velocity estimates that are produced are not unique or absolute. If a debris piece reaches its final location by ricochet or roll, then the velocity that is calculated will be lower than the true launch velocity. Further, if the debris piece reaches its final location via a launch angle that differs from the optimum, then the velocity that is estimated will also differ from the actual velocity.

The following equations may be used to estimate the velocity:

$$\text{Velocity (m/s)} = A_{wt}\exp(B_{wt}*\text{Range}) \quad (7)$$

$$A_{wtconcrete} = 5.41 + 1.79*[\ln(W)] + 0.049*[\ln(W)]^2 \quad (8)$$

$$A_{wtsteel} = 7.54 + 1.27*[\ln(W)] + 0.24*[\ln(W)]^2 \quad (9)$$

$$B_{wtconcrete} = 0.053*W^{-0.304} \quad (10)$$

$$B_{wtsteel} = 0.030*W^{-0.326} \quad (11)$$

In the above equations, W is the weight of the debris piece in grams and Range is the range in meters from the center of the structure to the debris in question. Enter equations (8) and (10) or (9) and (11) (depending on the type of material) and calculate A_{wt} and B_{wt}. Substitute these and the range into equation (7) to estimate the velocity.

For concrete debris, the equations are valid for weights between 45 grams and 45,000 grams. For steel debris, they are valid for weights between 10 grams and 4500 grams. The equations are valid for ranges between 50 and 1400 meters for concrete and 100 to 2000 meters for steel.

It should also be re-iterated that these equations provide approximations for the velocities and should be applied to far-field debris.

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